APPLICATIONS OF OPTOGALVANIC EFFECTS IN OPENING SWITCHES

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Abstract

Optogalvanic effects are changes in the electrical properties of a gas discharge caused by illumination with radiation at a wavelength corresponding to an atomic or molecular transition. The resurgence of interest in optogalvanic effects stems in a large measure from the unique properties of lasers such as: the high powers, the tunability, the narrow bandwidths, and the controllability of pulse parameters. The most significant application of the effects is as a sensitive diagnostic tool for characterizing discharge processes and rate constants. However, mild discharges are ignited and extinguished using optogalvanic effects. Selected transitions produce positive optogalvanic effects (a decreased impedance), while other transitions produce negative optogalvanic effects (an increased impedance). The resonant coupling of a laser and a discharge produces a large change in discharge current per absorbed unit of energy. Preliminary experiments in Ne positive column discharges are discussed. Potential limitations on electron and current density are also presented.

Introduction

Optogalvanic effects are changes in the electrical properties of a gas discharge caused by illumination with radiation at a wavelength corresponding to an atomic or molecular transition in the system. These effects were first observed by Penning over fifty years ago.[1] Recently there has been considerable interest in using the effects as a detection method in laser spectroscopy,[2,3,4] and as a gas discharge diagnostic.[5,6] Potential applications of optogalvanic effects in opening switches, first suggested by Guenther[7], are described in this paper.

Figure 1 is a schematic of an optogalvanic experiment. The effects are observed in the positive column of glow discharges as well as in the cathode region. The effects are observed using continuous wave lasers and pulsed lasers. The effects are observed using ultraviolet, visible, and infrared lasers. Optogalvanic effects in the positive column and applications of the effects in opening switches are discussed in this paper. Effects in the cathode region also deserve careful study, but they are not discussed in this paper.

Illumination of a gas discharge with radiation at a wavelength corresponding to an atomic transition of a material in the discharge causes perturbations of the steady state populations of two or more levels. In general the collisional ionization rates from different levels are unequal, so perturbations of the steady state populations of bound levels produce a perturbation of the ionization balance of the discharge. This in turn causes a change in the electrical properties of the discharge. Optogalvanic effects have been described as changes in E/p (electric field divided by pressure), as changes in current, or as changes in impedance. The choice of units in quantifying the effect is arbitrary.

Several different ionizing reactions play a role in producing the effects. Electron impact ionization,

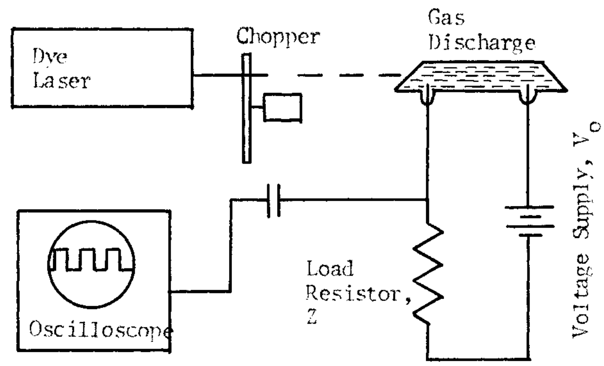

Fig. 1. Schematic of an Optogalvanic Experiment.

associative ionization, chemionization, and ionizing collisions between pairs of excited atoms are all important.

Optogalvanic effects correspond to increases or decreases in discharge current depending on the kinetics of the levels whose populations are perturbed by the laser. If the laser excites atoms from a level with a small probability of ionization to a level which has a larger probability of ionization, the discharge current will increase and the discharge voltage will decrease. Alternatively, if the laser excites atoms from a level with a large probability of ionization to a level with a small probability of ionization, the discharge current will decrease and the discharge voltage will increase. The latter situation often arises when the lower level is a long lived metastable level with a high probability of collisional ionization, and the upper level is a short lived resonance level with a high probability of radiative decay to the ground state.

A linear, steady state, analytical model of the optogalvanic effect has recently been proposed.[6] In the investigation the absolute magnitude of the optogalvanic effect of the 587.6 nm helium transition was measured as a function of positive column radius, column pressure, sustaining direct current, ballast resistance, and laser intensity. The model predicts the absolute magnitude of the effect as a function of the above experimental parameters.

In the model the rate equation problem is divided into two parts. The first part involves solving the rate equations exactly for a few levels whose populations are greatly perturbed by the laser. The solution is expressed as an ionization efficiency, the number of excess ion-electron pairs produced per absorbed photon. The second part of the problem involves describing the electrical response of the plasma to a small perturbation in the total ion production rate. It is solved by a linear, steady state perturbation analysis of the key rate equation or equations which describe the plasma. The solution is expressed as a collection efficiency, the number of excess electrons which flow through the ballast

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14. ABSTRACT
Optogalvanic effects are changes in the electrical properties of a gas discharge caused by illumination with radiation at a wavelength corresponding to an atomic or molecular transition. The resurgence of interest in optogalvanic effects stems in a large measure from the unique properties of lasers such as: the high powers, the tunability, the narrow bandwidths, and the controllability of pulse parameters. The most significant application of the effects is as a sensitive diagnostic tool for characterizing discharge processes and rate constants. However, mild discharges are ignited and extinguished using optogalvanic effects. Selected transitions produce positive optogalvanic effects (a decreased impedance), while other transitions produce negative optogalvanic. effec.ts (an increased impedance). The resonant coupling of a laser and a discharge produces a large change in discharge current per absorbed unit of energy.

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resistor per excess ion-electron pair produced in the plasma. The dynamic resistance of the plasma plays an important role in simplifying the linear analysis of the key rate equation(s). The dynamic resistance is difficult to calculate from first principles but is straightforward to measure. Each transition has a unique ionization efficiency, but the collection efficiency is a general property of the plasma. The quantum efficiency of an optogalvanic effect is the product of the ionization efficiency and the collection efficiency.

Two Step Ionization

The relative importance of ionization processes of electronically excited atoms versus direct electron impact ionization of ground state atoms determines the magnitude of optogalvanic effects and the usefulness of the effects in opening switches. The classic Schottky model of the positive column discharge neglects ionization from electronically excited levels! If the Schottky model were correct in this approximation we would expect that optogalvanic effects would always be small. This is not the case. It has become increasingly clear that ionization processes involving metastable atoms are the dominant source of ionization in positive column discharges over a wide range of operating conditions.[9] Typical two step ionization reactions in Neon (and other rare gases) are

$$e^- + Ne \rightarrow e^- + Ne^M \quad (1a)$$

or

$$e^- + Ne \rightarrow e^- + Ne^* \quad (1b)$$

$$Ne^* \rightarrow Ne^M + h\nu \quad (1c)$$

followed by

$$Ne^M + Ne^M \rightarrow Ne^+ + Ne + e^- \quad (2a)$$

or

$$e^- + Ne^M \rightarrow 2e^- + Ne^+. \quad (2b)$$

where Ne^M is a metastable Neon atom and Ne^* is an excited nonmetastable Neon atom. The two step processes dominate direct or single step ionization

$$e^- + Ne \rightarrow 2e^- + Ne^+ \quad (3)$$

because less energetic electrons are required. Electrons with energy above the first excitation potential will likely collide to produce an excited atom, often a metastable atom or an atom in a level that cascades to a metastable level, before the electrons gain sufficient additional energy to produce an ion directly. Electron energy distribution functions in rare gas positive column discharges are often not Maxwellian. The distribution function is depleted above the first excitation potential.[9] The distribution functions strongly favor atomic excitation over single step ionization.

If two step ionization is dominant over single step ionization we expect to find very high metastable atom densities in positive column discharges. Metastable densities are one to two orders of magnitude higher than ion densities.[9,10] Metastable densities are determined by a balance between electron impact production and several loss mechanisms including: diffusion to the wall, ionizing collisions between pairs of metastables, inelastic electron collisions, and superelastic electron collisions. At low current densities only diffusion is important and the metastable density varies linearly with the electron or ion density. Thus, two step ionization has a quadratic dependence on the electron density at low current densities. This dependence causes the negative dynamic resistance of the positive column discharges[9] which is discussed in a following paragraph. At moderate current densities the metastable density saturates due to collisions between pairs of metastables and inelastic electron collisions.[10] The reactions that saturate the metastable densities are the same reactions that provide ionization to sustain the discharge.

Laser Induced Depletion of Metastable Atoms

A laser can be used to deplete the metastable atom density in a discharge by exciting atoms from a metastable level to a radiating level. The optogalvanic effect produced corresponds to an increase in discharge voltage or a decrease in discharge current. Atoms are excited from a metastable level with a high probability of collisional ionization to a level with a high probability of radiative cascade to the ground state. Optogalvanic effects of this type were the first effects discovered; they can be quite strong even when produced by an incoherent source.[1,11,12] In Ne an effect of this type is produced by illuminating the discharge with radiation at 614.3 nm. The population of the metastable $1s_5$ level is decreased and the population of the $2p_6$ level is increased. An atom in the $2p_6$ level radiates spontaneously in 21.9 ns to the $1s_5$, $1s_4$, and $1s_2$ levels with branching ratios of 0.47, 0.11, and 0.42 respectively.[13] The $1s_4$ and $1s_2$ levels radiate to the ground state with lifetimes of 21 ns and 1.5 ns respectively.[13] Figure 2 illustrates this process. On the basis of the branching ratios the probability of destroying a metastable per absorbed photon is 0.53.

Radiation Trapping

In the discussion we have thus far ignored two important effects: radiation trapping of the VUV resonance radiation and collisional ionization of the resonance levels. Radiation trapping greatly lengthens the effective lifetime of an atom in the $1s_4$ and $1s_2$ levels. Consider a positive column discharge with a 0.1 cm radius at 1.0 Torr of pressure. The effective decay rate of the $1s_2$ level is calculated using the Biberman-Holstein theory of radiation trapping, as

$$A_T = 0.205\ A\ (\lambda/R)^{1/2} \quad (4)$$

where A_T is the trapped decay rate, A is the vacuum decay rate, λ is the wavelength and R is the column radius.[14] This formula includes collisional broadening of the transition but neglects Doppler broadening. It is accurate at pressures above 10.0 Torr, it provides a lower limit for the trapped decay rate at 1.0 Torr. The decay rate determined using this formula for the $1s_2$ level is $1.1 \times 10^6\ s^{-1}$. The decay rate of ths $1s_2$ level must be compared with the metastable diffusion rate to determine if the laser is effectively destroying excited atoms. The metastable diffusion rate at 1 Torr with a 0.1 cm column radius is $3.2 \times 10^4\ s^{-1}$.[14] Thus the resonance $1s_2$ level decays more than 35 times as fast as the metastable $1s_5$ level at low current densities. The ratio of the decay rates is likely between 50 and 100 when Doppler broadening is included in the radiation trapping calculation. From simple estimates it is apparent that it is possible to efficiently destroy metastable atoms using laser illumination.

The calculation also provides some insight into the maximum current density that might ultimately be switched. A current density 50 to 100 times that which saturates the density of metastable atoms will saturate the density of atoms in resonance levels. Saturation of the density of atoms in resonance levels means that such atoms have a high probability of collisional quenching rather than radiative decay to the ground state. The collisional quenching process will likely produce an ion. Thus it is not possible to lower the total ion production rate by pumping

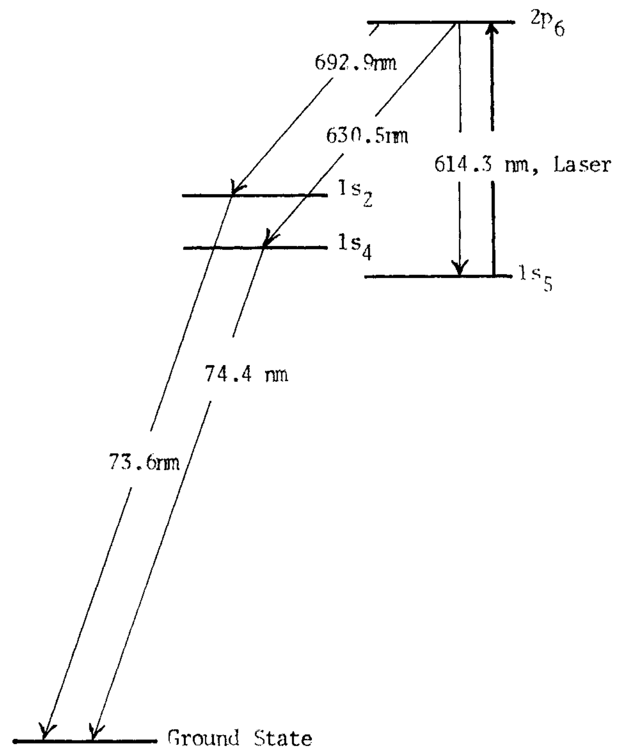

Fig. 2. Laser induced depletion of Ne $1s_5$ metastable atoms.

atoms from a metastable level to a resonance level if the population of the resonance level is saturated. The upper limit on the current density caused by saturation of resonance level populations may be 50 to 100 A/cm^2 in capillary discharges.

Model Calculations

The rate equation model of Ref. 6 provides an analytical expression for the magnitude of the optogalvanic effect on the 614.3 nm transition of Ne in the small signal or linear regime. The predicted magnitude is

$$\Delta v = -0.53\, Q \frac{Sn_e + 2TM}{D_M \left(\frac{2.4}{R}\right)^2} \frac{i_{dc}}{i\omega} \frac{\frac{dv}{di} Z}{\frac{dv}{di} + Z} \tag{5}$$

where Δv is the change in voltage across the positive column, Q is the number of photons absorbed per sec, S is the rate constant for electron impact ionization of the metastables, T is the rate constant for ionizing collisions between pairs of metastables, M is the density of metastables, D_M is metastable diffusion coefficient, R is the column radius, i_{dc} is the sustaining direct current, $i\omega$ is number of ions per sec diffusing to the wall, $\frac{dv}{di}$ is the dynamic resistance of the discharge, and Z is the ballast or load resistance. An experimental test of the model predictions is currently underway. In actual switching applications it cannot be assumed that the discharge responds linearly to the perturbation because the perturbation will not be small. The model must be extended to describe large perturbations.

Load Line Analysis

The negative dynamic resistance of positive column discharges caused by the quadratic dependence of two step ionization on the electron density[8] can be used to some advantage in switching applications. The optogalvanic effect must eliminate stable operating points on the load line to extinguish a discharge. Consider the load line and the voltage versus current plot of Fig. 3. Point 1 is an unstable operating point because the magnitude of the negative dynamic resistance is larger than the magnitude of the positive load resistor, Z. Point 2 is a stable operating point. The optogalvanic effect can be used to extinguish the discharge by increasing the discharge voltage at fixed current. The intersection points labeled 1 and 2 on the load line will coalesce and then disappear as the discharge voltage versus current curve is displaced upward.

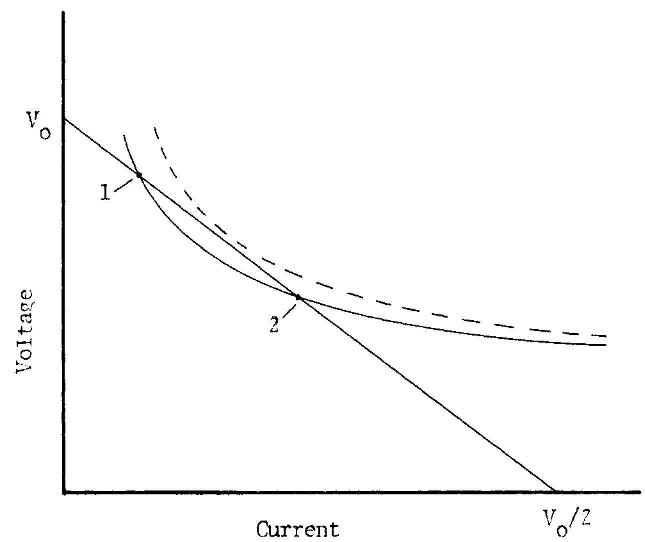

Fig. 3. Voltage verses current curve of a positive column discharge and a load line. The dashed line illustrates the shift in the voltage-current curve necessary to extinguish the discharge.

In summary, applications in opening switch technology of optogalvanic effects in positive column discharges are described. Optogalvanic effects, or laser induced perturbations of the ionization balance of a discharge, can be substantial because ionization processes involving metastables are the dominant source of ionization in positive column discharges. The metastable population can be depleted by exciting atoms from the metastable level to a level which radiatively decays to the ground state. The effects of trapping of resonance radiation and collisional ionization of atoms in resonance levels provide an upper limit on the current density that may ultimately be switched using optogalvanic effects.

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